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FORM-FUNCTIONS FOR THE IBHVG CODE

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The form-functions, methods of calculating the mass fraction burned given the depth burned, are developed for the ten propellant grain geometries available in the IBHVG code, a frequently used interior ballistic computer program. The FORTRAN coding embodying the computations is included.

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I. INTRODUCTION

This report documents the form-functions developed for the interior ballistics computer code Interior Ballistics of High-Velocity Guns (IBHVG), a FORTRAN program used in the Interior Ballistics Division of the Ballistic Research Laboratory. IBHVG, based on the Baer-Frankle code[1], will itself be the subject of a forthcoming report.

A "form-function" is any computational scheme for determining either surface area, volume, or fraction burned for a burning propellant grain at any instant from ignition to extinction based on initial dimensions and depth burned. Either surface area or fraction burned is generally required in interior ballistic calculations. The IBHVG code does not use surface area so the form-functions described below omit area derivation. Also, the traditional assumptions are made that all grain surfaces erode at the same rate and all the perforations are of equal diameter.

A variety of approaches to a number of grain geometries have been taken in the past[2,3]. Stals, for example, not only deals with detailed analyses of different grain types, but contains a wealth of background information, history of attacks to the problem, and an extensive bibliography. While this report does not attempt to supplant previous efforts, it presents some novel treatments which may prove applicable to codes other than IBHVG. For example, the analyses of the seven- and nineteen-perforated cases are based on a method of dealing with general cylindrical grains[4]. This method enables handling grains with unequal webs.

The FORTRAN coding embodying the methods of calculations will be discussed in parallel with the development of all algorithms for ease of

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[1] *P. G. Baer, and J. M. Frankle, "The Simulation of Interior Ballistic Performance of Guns by Digital Computer Program," USA Ballistic Research Laboratories Report 1183, USA Ballistic Research Laboratories, APG, MD, December 1962.*

[2] *J. Corner, "Theory of the Interior Ballistics of Guns," John Wiley & Sons, New York, 1950, pp. 30-35.*

[3] *J. Stals, "Form-Functions for Multicomponent Propellant Charges Including Inhibited Grains and Sliver Burn," Materials Research Laboratories Technical Note 371, Materials Research Laboratories, Maribyrnong, Victoria, Australia, September 1975.*

[4] *F. R. Lynn, "Development of General Form-Functions for Multiperforated Cylindrical Propellant Grains," Ballistic Research Laboratory Memorandum Report ARBRLMR03014, Ballistic Research Laboratory, USA ARRADCOM, APG, MD, March 1980.*

understanding. Also, FORTRAN computational hierarchy is followed throughout the text. A comprehensive listing of the referenced subroutines will be found in APPENDIX A.

II. SUBROUTINE ORGANIZATION

The result of the form-function calculations in IBHVG is the fractions burned, at any instant, for the M propellants comprising the charge, where $1 \le M \le 5$. At each time step, a call is made to a single subroutine, FORMT, which either performs the required operations or, in the case of seven- or nineteen-perforated grains, calls auxiliary routines GENIS and GENOS. APPENDIX A contains listings for these three subroutines.

APPENDIX B notes all important input, output, and control variables used. Most are passed through COMMON, although a few are local. No other COMMON variables pertain to FORMT operation.

Subroutine FORMT is called whenever the calling program requires the fractions burned, the Z array, of the M propellants being burned. A glance at the listing reveals that FORMT is essentially one large loop, processing each of the M propellants in turn. All computations for the Jth propellant are bypassed if either it is entirely consumed, that is,

$$Z(J) \geq 1$$

or if logic elsewhere in IBHVG dictates that the condition flag

$$ICFLAG(J) = 0$$

which signifies that the ignition criterion for the Jth propellant has not been met. However, if the propellant has ignited but is not yet completely burned, execution continues. The depth burned for propellant J is extracted from the Y array, having been calculated elsewhere prior to entrance to FORMT, and twice this value is stored in U. Next, N(J), the grain code for propellant J in Table 1 is examined, and a branch taken to the appropriate area of FORMT. There, the fraction burned, Z(J), is determined based on U, initial grain dimensions, and various control variables, followed by a jump to the bottom of the loop. After all M propellants have been processed, a return is made from FORMT to the calling routine.

As Table 1 notes, there are ten different grain types dealt with by IBHVG. The remainder of the report will be concerned with considering the types in turn, devising a method of finding Z for them at any instant, and developing the FORMT coding based on these calculations.

III. GRAIN TYPE 1: SEVEN-PERFORATED CYLINDER

An end view of this grain appears in Figure 1. It is a cylinder pierced longitudinally by seven cylindrical holes arranged at the center

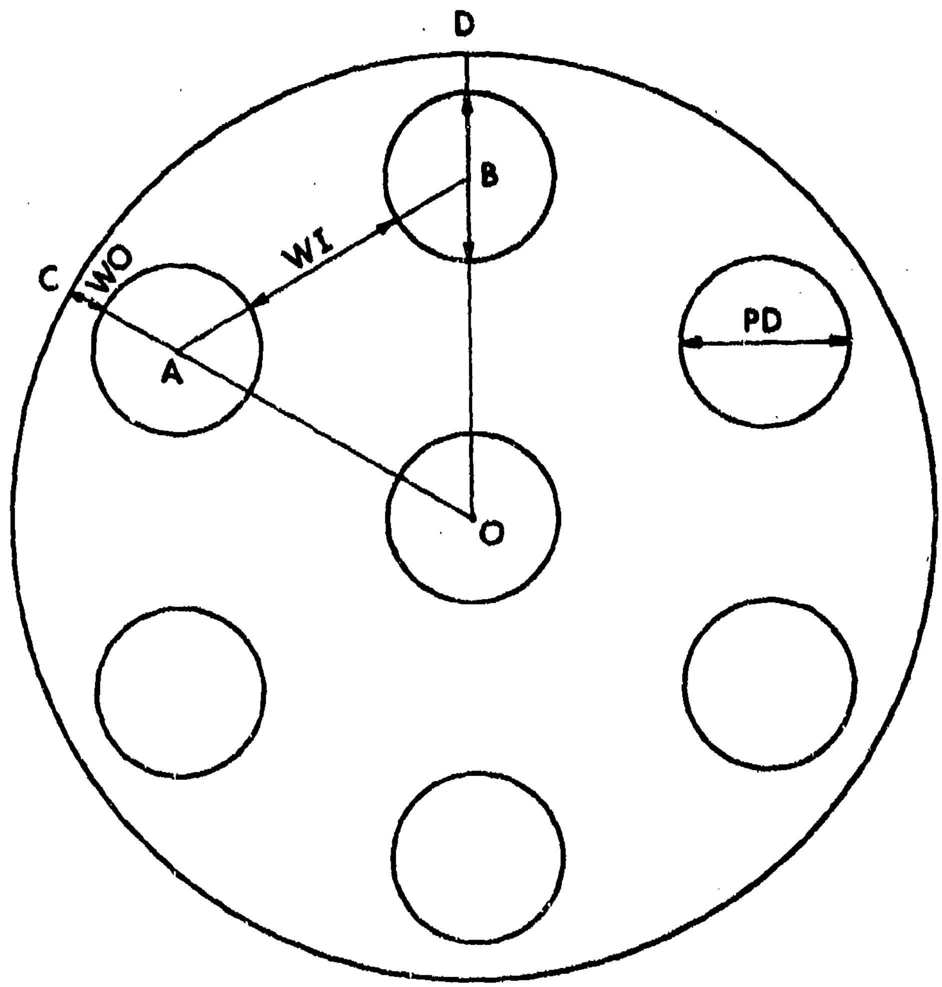

Figure 1. Seven-Perforated Grain -- End View

TABLE 1. IBHVG GRAIN GEOMETRIES AND CODES

GRAIN CODE	GEOMETRY
1	7-perforated cylinder
2	1-perforated cylinder
3	cord
4	rectangular strip
5	sphere
6	slotted tube
7	37-perforated hexagonal
8	19-perforated hexagonal
9	19-perforated cylinder
10	7-perforated hexagonal

and vertices of a regular hexagon. Initially, suppose the grain to have length GL(J), diameter D(J), perforation diameter PD(J), inner web WI(J), and outer web WO(J).

On the first call to FORMT, i.e., at the beginning of the first time step, COMMON variable I is set to 0. On succeeding passes, I will be greater than zero, thereby forcing a branch to line 50, bypassing the initialization section which is described next.

First, the middle web, WM(J) is zeroed as it is not used by this grain type. Then the diameter is recomputed to absorb any inconsistencies in grain dimensions. Figure 1 makes the calculation

$$D(J) = 3 \cdot PD(J) + 2 \cdot (WI(J) + WO(J)), \tag{1}$$

clear. Next, the initial grain volume is determined and stored in VO(J). The end area, E, of the grain is given by

$$E = \pi/4 \cdot D(J)^2 - 7 \cdot \pi/4 \cdot PD(J)^2, \tag{2}$$

so the initial volume is

$$\begin{aligned} VO(J) &= GL(J) \cdot E \\ &= .25 \cdot \pi \cdot GL(J) \cdot (D(J)^2 - 7 \cdot PD(J)^2). \end{aligned} \tag{3}$$

Note that we assume π is passed through COMMON Variable PI.

The method developed in Reference 4 is employed and, in what follows, its notation and nomenclature are used freely. For purposes of calculating the end-area of the grain, it is partitioned into one class of outer slivers congruent to ABDC and one class of inner slivers congruent to OAB.

Array IFLAG is the branch-flag array and two positions are initialized to -1 for this, the Jth propellant.

Array SF is the "side" array. Letting

$$WW = WI(J) + PD(J) \tag{4}$$

represent the distance between centers of adjacent perforations, all three sides of each sliver in both classes are set to length WW.

The last calculation in the initialization section is the determination of the grain's web, the shortest distance through the grain to be broached as the grain burns. This is given by

$$WEBC(J) = \min (WO(J), WI(J), GL(J)), \tag{5}$$

the length being included to account for very short grains.

The post-initialization coding starts at line 50. The reduced grain length, reduced grain diameter, and increased perforation diameter are

$$\begin{aligned} GRL &= \max (GL(J) - U, 0) \\ OD &= D-U \\ PRFD &= PD+U, \end{aligned} \tag{6}$$

respectively, the maximum being taken to guarantee a non-negative grain length. If

$$0 \le U \le WEBC(J),$$

the web is not broached and we determine end-area of the grain, E, by the same method as in the initialization section, so

$$E = \pi/4 \cdot OD^2 - 7 \cdot \pi/4 \cdot PRFD^2 \tag{7}$$

yielding

$$Z(J) = 1 - GRL \cdot E/VO(J). \tag{8}$$

However, if

$$WEBC(J) < U,$$

we branch to line 60 and employ routines GENIS and GENOS as described in Reference 4 with one minor modification. Since IBHVG does not use grain surface area, the argument to return that quantity is not present in the call and the coding in GENIS and GENOS which yields sliver surface area is commented out as can be seen from APPENDIX A. The AW array is the work array and sliver volumes for the inner and outer slivers of the Jth propellant are returned through the appropriate cells in array GV. Total sliver volume of a given class is six times the volume of each sliver, yielding

$$Z(J) = 1 - 6 \cdot (GV(1,J) + GV(2,J))/VO(J). \tag{9}$$

A branch is then made to the bottom of the loop.

IV. GRAIN-TYPE 2: SINGLE-PERFORATED CYLINDER

Initially, this grain is a cylinder of length GL(J) and diameter D(J) pierced by a cylindrical hole of diameter PD(J), the centers of the two cylinders coinciding. Let the web be WI(J).

As with the case of the seven-perforated cylinder, an initialization section is processed if I = 0. The middle web, WM(J), and outer web, WO(J), are zeroed as they are unused and the diameter recalculated as

$$D(J) = PD(J) + 2 \cdot WI(J), \tag{10}$$

to absorb any error in grain dimensions. Then

$$WEBC(J) = \min\ (WI(J),\ GL(J)) \tag{11}$$

is twice the depth burned at grain extinction. Letting E represent the initial end area of the grain, we have

$$E = \pi/4 \cdot D(J)^2 - \pi/4 \cdot PD(J)^2, \tag{12}$$

and the initial volume is

$$VO(J) = GL(J) \cdot E$$
$$= \pi/4 \cdot GL(J) \cdot (D(J)^2 - PD(J)^2). \qquad (13)$$

The factor $\pi/4$ is not present in the coding as it will cancel in the calculation of Z(J).

The post-initialization coding starts at line 190. The end-area, E, of the grain burned to a depth of 1/2 U must be determined. First, it is cleared by

$$E = 0.$$

If

$$0 \leq U \leq WEBC(J),$$

then we override this value of zero for E. The reduced grain length, reduced grain diameter, and increased perforation diameter are

GL(J)-U
D(J)-U
PD(J)+U,

respectively, so, as above,

$$E = \pi/4 \cdot (D(J) - U)^2 - \pi/4 \cdot (PD(J) + U)^2$$
$$= \pi/4 \cdot ((D(J) - U)^2 - (PD(J) + U)^2), \qquad (14)$$

and fraction burned is

$$Z(J) = 1 - E \cdot (GL(J) - U)/VO(J). \qquad (15)$$

Note that the factor $\pi/4$ in the calculation of E is absent in the coding as it would cancel in the Z(J) calculation.

V. GRAIN TYPE 3: CORD

Initially, this grain is a solid cylinder with length GL(J) and diameter D(J).

If COMMON variable I=0, indicating the first call to FORMT, an initialization section is processed. The perforation diameter and inner, middle, and outer webs are zeroed for this, the Jth propellant, as these quantities are unused. The initial volume

$$VO(J) = GL(J) \cdot \pi/4 \cdot D(J)^2 \tag{16}$$

is that of a right circular cylinder. In the coding, the $\pi/4$ is omitted because it will cancel in the calculation of Z(J).

Post-initialization code starts at line 220. The reduced grain dimensions

GL(J)-U
D(J)-U

are used to produce the fraction burned

$$Z(J) = 1 - \max(GL(J)-U,0) \cdot \max(D(J)-U,0)^2/VO(J) \tag{17}$$

where the $\pi/4$ factor is absent, having cancelled with a like factor in VO(J).

VI. GRAIN TYPE 4: RECTANGULAR STRIP

Initially, this grain is a solid rectangular parallelopiped with length GL(J) width D(J), and depth WI(J).

As above, variable I = 0 signals processing of an initialization section. First, all grain dimensions not used are zeroed and the initial grain volume

$$VO(J) = GL(J) \cdot D(J) \cdot WI(J), \tag{18}$$

is determined.

The post-initialization code starts at line 440. The reduced grain dimensions, namely,

GL(J)-U
D(J)-U
WI(J)-U,

are multiplied together to produce the volume. And thus the fraction burned is

$$Z(J) = 1 - \max(GL(J)-U) \cdot \max(D(J)-U) \cdot \max(WI(J)-U)/VO(J) \quad (19)$$

where the maxima are taken with 0 to guarantee a non-negative grain volume.

VII. GRAIN TYPE 5: SPHERE

Initially, this grain is a solid sphere of diameter D(J).

On the initialization pass, signaled by I = 0, all grain dimensions except grain diameter are zeroed because they are unused.

The reduced grain diameter is

$$D(J)-U.$$

Thus fraction burned is

$$\begin{aligned} Z(J) &= 1 - 1/6 \cdot \pi \cdot \max(D(J) - U,0)^3/(1/6 \cdot \pi \cdot D(J)^3) \quad (20) \\ &= 1 - (\max(D(J) - U,0)/D(J))^3, \end{aligned}$$

where the maximum is taken to guarantee a non-negative reduced grain diameter.

VIII. GRAIN TYPE 6: SLOTTED TUBE

An end view of this grain appears in Figure 2. It is an ordinary single-perforated grain with a slot, the sides of which are parallel. Initially, suppose the grain to have length GL(J), diameter D(J), web WI(J), perforation diameter PD(J), and slot width WM(J).

As with the other grain types, an initialization section is processed if COMMON variable I = 0. First, the unused dimension WO(J) zeroed. Let

$$PRFD = .5 \cdot WM(J), \quad (21)$$

be half the slot width,

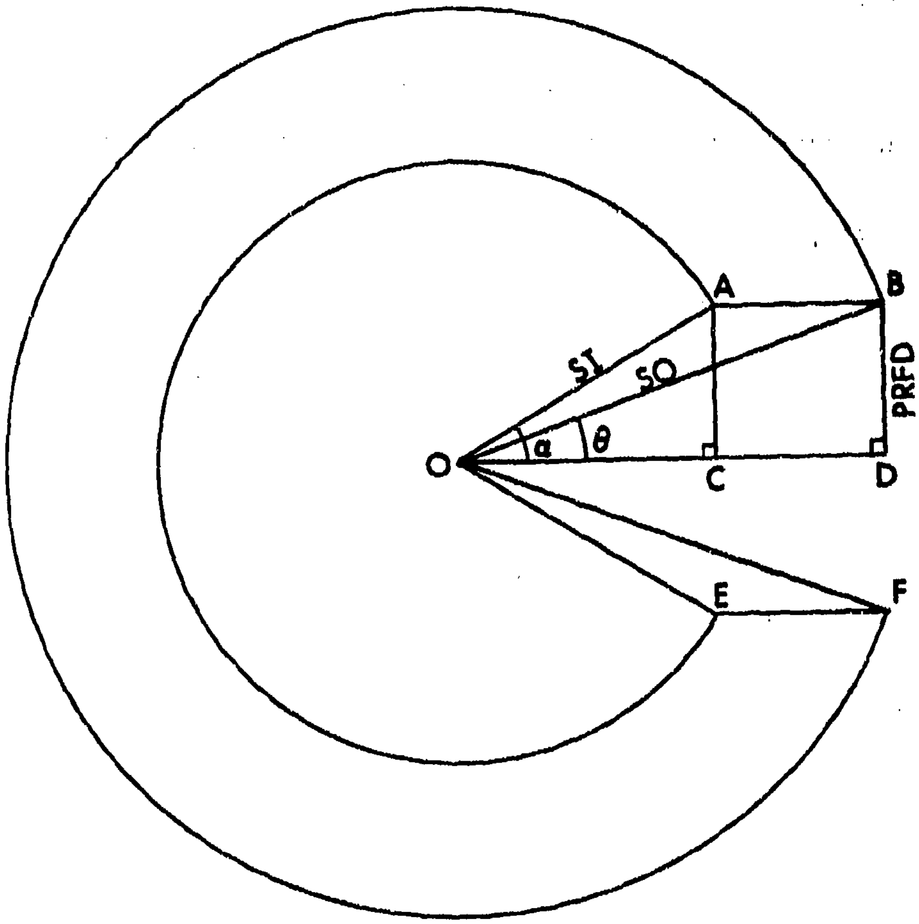

Figure 2. Slotted Tube Grain -- End View

$$SO = .5 \cdot D(J), \tag{22}$$

be the grain radius, and

$$SI = .5 \cdot PD(J), \tag{23}$$

be the perforation radius. In right triangles OBD and OAC we have

$$\begin{aligned} \theta &= \pi/2 - \mathrm{acos}(PRFD/SO) \\ \alpha &= \pi/2 - \mathrm{acos}(PRFD/SI), \end{aligned} \tag{24}$$

respectively. As before, the code assumes PI contains π. Denote by E the end-area of the grain; then

$$\begin{aligned} E = {} & \text{area reflex sector BOF} \\ & - \text{area reflex sector AOE} \\ & - 2 \cdot \text{area triangle AOB} \\ = {} & 1/2 \cdot (2\pi - 2\theta) \cdot SO^2 - 1/2 \cdot (2\pi - 2\alpha) \cdot SI^2 \\ & - 2 \cdot 1/2 \cdot PRFD \cdot (SO \cdot \cos(\theta) - SI \cdot \cos(\alpha)) \\ = {} & (\pi - \theta) \cdot SO^2 - (\pi - \alpha) \cdot SI^2 \\ & - PRFD \cdot (SO \cdot \cos(\theta) - SI \cdot \cos(\alpha)). \end{aligned} \tag{25}$$

Thus initial volume is

$$VO(J) = GL(J) \cdot E. \tag{26}$$

Finally,

$$WEBC(J) = \min(GL(J), WI(J)), \tag{27}$$

is twice the depth burned at grain extinction.

The post-initialization section of coding starts at line 510. The end-area of the grain, E, is cleared by

$$E = 0.$$

If

$$WEBC(J) < U,$$

then the grain is extinguished and a branch is taken to line 520, producing a fraction burned of 1. Otherwise, let

$$PRFD = .5 \cdot (WM(J) + U), \tag{28}$$

be half the new slot width,

$$SO = .5 \cdot (D(J) - U), \tag{29}$$

be reduced grain radius,

$$SI = .5 \cdot (PD(J) + U) \tag{30}$$

be perforation radius, and

$$GRL = GL(J) - U, \tag{31}$$

be reduced grain length. Then θ, α, and E are calculated as done in the initialization section and fraction burned is

$$Z(J) = 1 - E \cdot GRL/VO(J). \tag{32}$$

IX. GRAIN TYPES 7, 8, AND 10: ROUNDED-HEXAGONAL

Figure 3 depicts one-sixth of a rounded-hexagonal grain with nineteen perforations. Let grain length be GL(J), all inner webs be WI(J), the outer web WO(J), and perforation diameter PD(J). Note that the rounded "corners" are bounded by inside and outside circular arcs of radii 1/2 · PD(J) and WO(J) + 1/2 · PD(J), respectively, as shown in sector CDE.

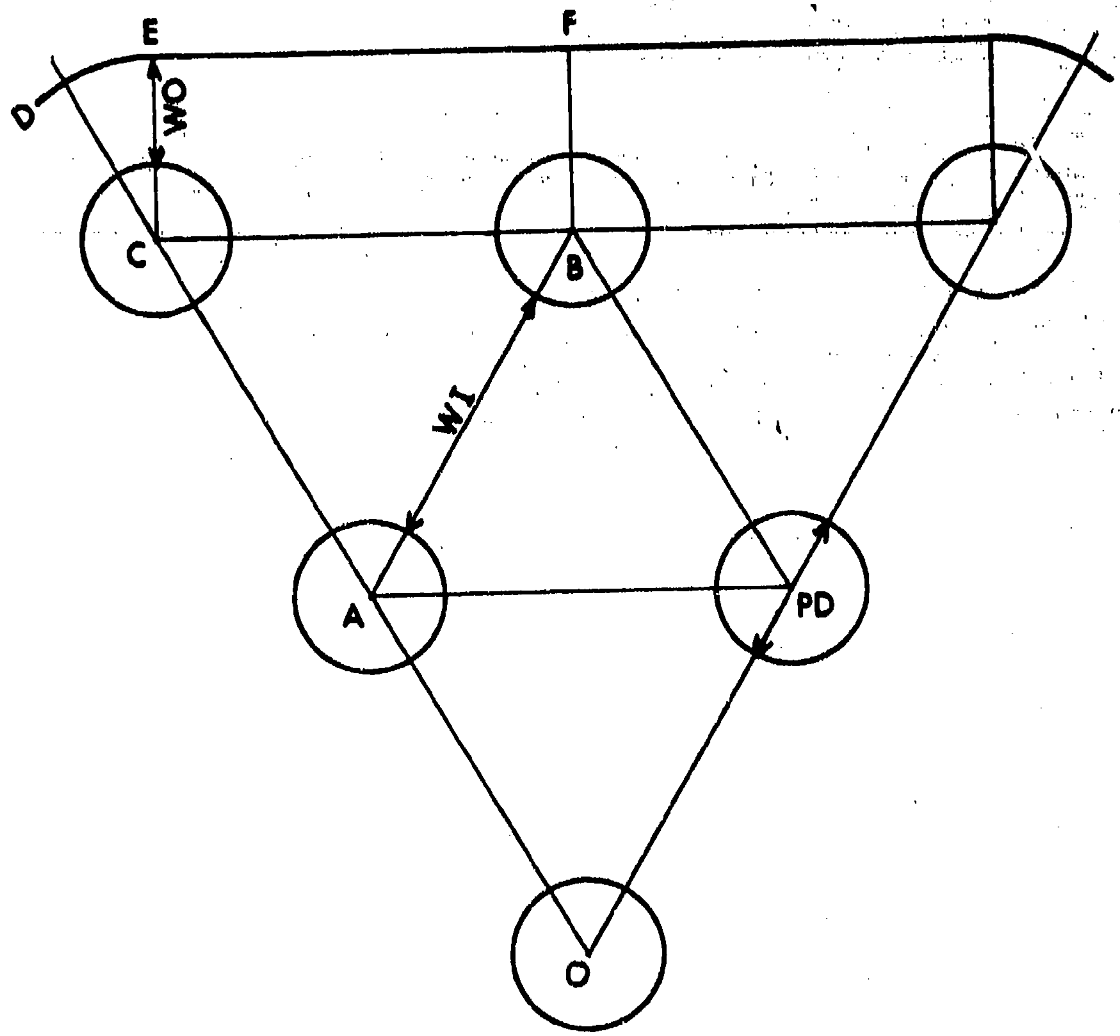

Figure 3. One-Sixth of Hex Grain -- End View

The 7-, 19- and 37-perforated hexagonal grains are but special members of a family. By induction on K, the number of hexagonal rings of perforations, we have

$$
\begin{aligned}
NP &= \text{number of perforations} = 3K^2 + 3K + 1 \qquad (33)\\
SI &= \text{number of inner slivers} = 6K^2\\
SO &= \text{number of outer slivers} = 6K\\
&\ \text{number of corner slivers} = 12,
\end{aligned}
$$

for $K \geq 0$. The inner slivers are all congruent to the area within ABC, the outer slivers to the area within BCHF, and the corners to CDE. Routine FORMT currently handles cases K = 1, 2, and 3 yielding, respectively, NP = 7, 19, and 37, SI = 6, 24, and 54, and SO = 6, 12, and 18.

Entry for hex grains is made at statements 240, 250, or 600 in FORMT where SO and SI are set to the appropriate values and a branch taken to line 260. Here WW is the distance between centers of adjacent perforations and WW2 is its square, PRFD is the increased perforation diameter and PRFD2 its square, GRL is the reduced grain length, and WOD is the outer web. The end area of the grain, E, is initially cleared to zero.

Figure 4 shows an inner sliver during burning. By definition of cosines,

$$
\begin{aligned}
\theta &= 2 \cdot \text{acos}(\min(1, \overline{CL}/\overline{CJ})) \qquad (34)\\
&= 2 \cdot \text{acos}(\min(1, WW/PRFD)),
\end{aligned}
$$

where the minimum is taken with 1 in case θ is degenerate. Figure 5 shows an outer sliver burning. By definition of cosines,

$$
\begin{aligned}
\alpha &= \text{acos}(\min(1, \overline{EC}/\overline{CM})) \qquad (35)\\
&= \text{acos}(\min(1, (PD(J) + 2 \cdot WOD-U)/PRFD)),
\end{aligned}
$$

where the minimum is taken with 1 in case α is degenerate. These angles are sufficient to calculate E.

Consider the twelve corners. If

$$WOD \leq U,$$

they are completely consumed and their contribution to E is zero.

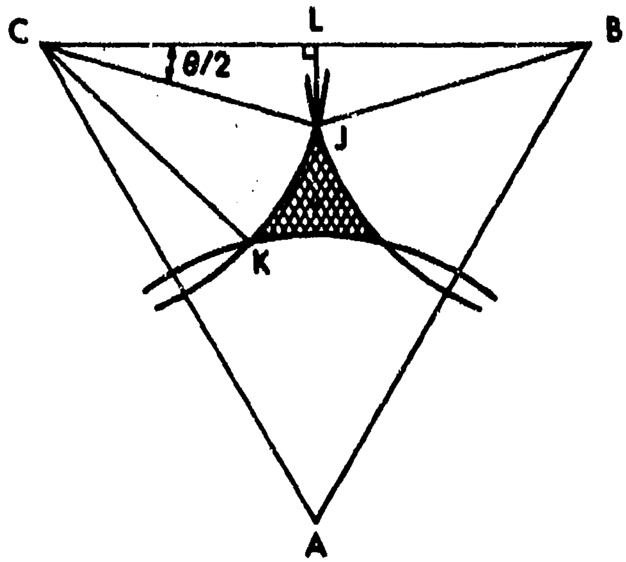

Figure 4. Hex Grain -- Inner Sliver

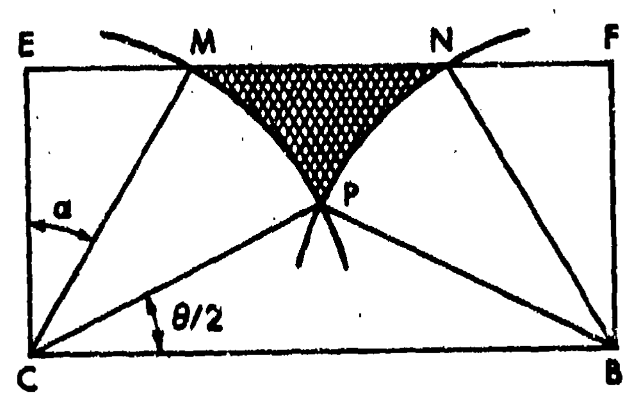

Figure 5. Hex Grain -- Outer Sliver

Otherwise, by subtracting the area of concentric circular sectors, and recalling that π is in PI,

$$E = 12 \cdot (1/2 \cdot \pi/6 \cdot (1/2 \cdot PD(J) + WOD - 1/2 \cdot U)^2 \tag{36}$$

$$- 1/2 \cdot \pi/6 \cdot (PRFD/2)^2$$

$$= .25 \cdot \pi \cdot ((PD(J) + 2 \cdot WOD - U)^2 - PRFD^2).$$

Consider now the inner slivers. A DATA statement provides values of square root of 3 in RT and $\pi/3$ in PI3, variables required for the remainder of this analysis. If

$$\pi/3 \leq \theta,$$

then all inner slivers are consumed so a branch is taken to line 270. Otherwise, the area contribution of the SI inner slivers must be added to E. Hence, referring to Figure 4,

$$E = E + SI \cdot (\text{area inner sliver}) \tag{37}$$

$$= E + SI \cdot (\text{area traingle ABC} - 3 \cdot \text{area triangle JBC}$$

$$- 3 \cdot \text{area sector JCK})$$

$$= E + SI \cdot (1/2 \cdot WW \cdot (1/2 \;\; WW \sqrt{3})$$

$$- 3 \cdot 1/2 \cdot WW \cdot (1/2 \cdot PRFD \cdot \sin(\theta/2))$$

$$- 3 \cdot 1/2 \cdot (\pi/3 - \theta) \cdot (PRFD/2)^2).$$

Then, by substitution in the line with sin (θ/2) using

$$WW = PRFD \cdot \cos(\theta/2), \tag{38}$$

and recalling the half-angle formula for sin,

$$E = E + SI \cdot .25 \cdot (WW^2 \cdot \sqrt{3} - 1.5 \cdot PRFD^2 \cdot (\sin(\theta) + \pi/3 - \theta)). \tag{39}$$

Lastly, consider the outer slivers. When

$$\alpha + \theta/2 \geq \pi/2,$$

or, equivalently

$$\alpha \geq 1/2\ (\pi-\theta),$$

then the outer slivers are extinguished and a branch is taken to line 280. Otherwise, the area contribution of the SO o `er slivers must be added to E. Hence,

$$E = E + SO \cdot (\text{area outer sliver}) \tag{40}$$

$$= E + SO \cdot (\text{area rectangle BCEF - area triangle BCP}$$

$$- 2 \cdot \text{area triangle MEC} - 2 \cdot \text{area sector MCP})$$

$$= E + SO \cdot (WW \cdot (PD(J) + 2 \cdot WOD\text{-}U)/2$$

$$- 1/2 \cdot WW \cdot (1/2 \cdot PRFD \cdot \sin(\theta/2))$$

$$- 2 \cdot 1/2 \cdot (PD(J) + 2 \cdot WOD\text{-}U)/2 \cdot (1/2 \cdot PRFD \cdot \sin(\alpha))$$

$$- 2 \cdot 1/2 \cdot (\pi/2 - \alpha - \theta/2) \cdot (PRFD/2)^2)$$

$$= E + SO \cdot .125 \cdot (2 \cdot (2 \cdot WOD + PD(J)\text{-}U) \cdot (2 \cdot WW - PRFD \cdot \sin(\alpha))$$

$$- PRFD^2 \cdot (\sin(\theta) + \pi - 2 \cdot \alpha - \theta)).$$

This concludes the calculation of E. If variable $I > 0$, then the initialization section is bypassed and $Z = 1 - E \cdot GRL/VO(J)$. Otherwise, the grain diameter D(J) is recalculated for printout purposes. As in the case of the other grain types, the initial grain volume must be computed.

Initially, we have

$$U = 0$$
$$\alpha = 0$$
$$\theta = 0$$
$$PRFD = PD(J),$$

and all slivers and corners are present. This implies

$$E = .25 \cdot \pi \cdot ((PD(J) + 2 \cdot WOD)^2 - PD(J)^2) \tag{41}$$

$$+ SI \cdot .25 \cdot (WW^2 \cdot \sqrt{3} - 1.5 \cdot PD(J)^2 \cdot \pi/3)$$

$$+ SO \cdot .125 \cdot (2 \cdot (2 \cdot WOD + PD(J)) \cdot 2 \cdot WW - PD(J)^2 \cdot \pi)$$

$$= \pi \cdot WOD \cdot (WOD + PD(J)) + .25 \cdot SI \cdot WW^2 \cdot \sqrt{3}$$

$$- .125 \cdot \pi \cdot (SO + SI) \cdot PD(J)^2 + SO \cdot WW \cdot (WOD + 1/2\ PD(J)),$$

and

$$VO(J) = GL(J) \cdot E. \tag{42}$$

Finally, a check must be made to see whether the outer sliver remains within its original bounds, for if it does not, the above analysis is invalid. That is, the point P in Figure 5 must not reach the midpoint of $\overline{BC}$ before the perforation centered at C does. Equivalently, we must have

$$\overline{EC} \geq 1/2\ \overline{CB} - 1/2\ PD(J) \tag{43}$$

$$WOD + 1/2\ PD(J) \geq 1/2\ WI\ (J)$$

$$2 \cdot WOD + PD(J) \geq WI(J),$$

and conversely. Otherwise, FORMT will stop with an error message.

X. GRAIN TYPE 9: NINETEEN-PERFORATED CYLINDER

Initially, this grain is a cylinder pierced by nineteen uniform cylindrical perforations. An end view is shown in Figure 6. Its length is GL(J), diameter D(J), and perforation diameter PD(J). It is characterized by three webs: inner, WI(J); middle, WM(J); and outer, WO(J).

If COMMON variable I is greater than zero, the initialization section is bypassed by a branch to line 320. Otherwise, the grain diameter is recalculated to absorb any inconsistencies as

$$D(J) = 5 \cdot PD(J) + 2 \cdot (WI(J) + WM(J) + WO(J)), \tag{44}$$

and the grain volume is computed by

$$VO(J) = GL(J) \cdot (\pi/4 \cdot D(J)^2 - 19 \cdot \pi/4 \cdot PD(J)^2) \tag{45}$$

$$= .25 \cdot \pi \cdot GL(J) \cdot (D(J)^2 - 19 \cdot PD(J)^2).$$

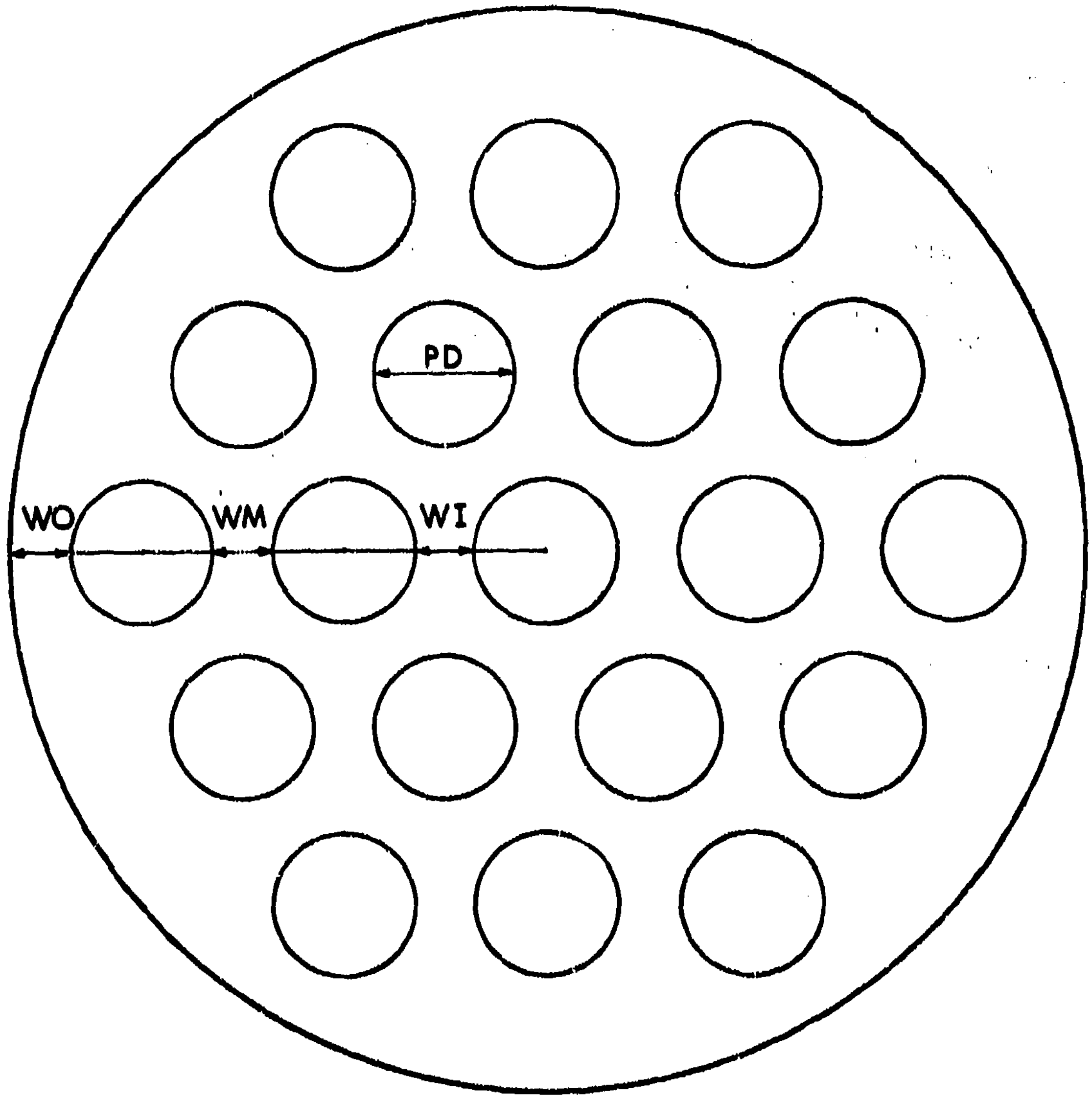

Figure 6. Nineteen-Perforated Grain -- End View

The remainder of the initialization section and the whole of the post-initialization coding is drawn directly from the worked example, Section IV, in Reference 4 with IFLAG, SF, AW, GV being the flag, side, work, and volume arrays. The only novelties are the addition of an additional subscript for the Jth propellant and the removal of the surface area computation. The latter was discussed in the case of the seven-perforated grain, above.

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4. Franz R. Lynn, "Development of General Form-Functions for Multi-perforated Cylinderical Propellant Grains," Ballistic Research Laboratory Memorandum Report ARBRLMR03014, Ballistic Research Laboratory, USA ARRADCOM, APG, MD, April 1980.

APPENDIX A

LISTING OF FORM-FUNCTION SUBROUTINES

```
C      FORMT.007       29-APR-82
       SUBROUTINE FORMT
       COMMON/IGNITE/ICFLAG(5)
       COMMON/RUNBLK/XC(20),PR(20),N(5),GTY(5),C(5),
      $F(5),TO(5),ALP(5),BET(5),GA(5),COV(5),RHO(5),
      $GL(5),D(5),PD(5),WI(5),WM(5),WO(5),G1,G2(2),
      $XMJZ,VO,TW,DG,DL,GLR,CV,DT,WP,NPR,M,LVSPK,ICODE(5),
      $THRESH(5),IBRHO(5),BRHP(5,5),BRMR(5,5),AVEWEB(5)
       COMMON/XTRA/PT(2),PB(2),XLST,PRLST,DEN2,H(2),RES,AGW,
      $I,CT,AP,PM,PBR(2),DEN1,HCL,AC(5),BC(5),CC(5),DC(5),
      $EC(5),Z(5),PDV,FHL,PTPP,PBPP,HPP,PBRPP,TPP,VPP,XPP,APP,
      $APK,Z1PP,Z2PP,Z3PP,Z4PP,Z5PP,COEFF,DEN3,CTN,PI,VO(5),
      $XR,MM,Y(8),DY(8)
       DIMENSION WEBC(5),SF(3,4,5),AW(4,4,5),IFLAG(4,5),GV(4,5)
       DATA RT/1.732050808/,PI3/1.047197551/
C
C***   FIND FRACTIONS BURNED Z(J) FOR J=1,2,...,M PROPELLANTS
       DO 1000 J=1,M
C
C***   BYPASS IF JTH PROPELLANT UNIGNITED OR EXTINGUISHED
       IF(Z(J).GE.1..OR.ICFLAG(J).EQ.0) GOTO 1000
C
C***   SET U = 2 X DEPTH BURNED & BRANCH ON GRAIN TYPE
       U=2.*Y(J+3)
       GOTO (20,180,210,430,450,500,250,240,310,600),N(J)
C
C***   CODE 1: 7-PERF GRAIN
 20    IF(I.GT.0) GOTO 50
       WM(J)=0.
       D(J)=3.*PD(J)+2.*(WI(J)+WO(J))
       VO(J)=.25*PI*GL(J)*(D(J)**2-7.*PD(J)**2)
       IFLAG(1,J)=-1
       IFLAG(2,J)=-1
       WW=WI(J)+PD(J)
       DO 30 K=1,3
       SF(K,1,J)=WW
       SF(K,2,J)=WW
 30    CONTINUE
       WEBC(J)=AMIN1(WO(J),WI(J),GL(J))
 50    GRL=AMAX1(GL(J)-U,0.)
       DD=D(J)-U
       PRFD=PD(J)+U
       IF(U.GT.WEBC(J)) GOTO 60
       E=.25*PI*(DD**2-7.*PRFD**2)
       Z(J)=1.-GRL*E/VO(J)
       GOTO 1000
 60    CALL GENIS(SF(1,1,J),AW(1,1,J),PRFD,GRL,IFLAG(1,J),GV(1,J))
       CALL GENOS(SF(1,2,J),AW(1,2,J),PRFD,GRL,.5*DD,IFLAG(2,J),GV(2,J))
       Z(J)=1.-6.*(GV(1,J)+GV(2,J))/VO(J)
       GOTO 1000
C
C***   CODE 2: 1-PERF GRAIN
 180   IF(I.GT.0) GOTO 190
       WM(J)=0.
       VO(J)=0.
       D(J)=PD(J)+2.*WI(J)
       WEBC(J)=AMIN1(GL(J),WI(J))
```

```
      VO(J)=GL(J)*(D(J)**2-PD(J)**2)
 190  E=0.
      IF(U.LE.WERC(J)) E=(D(J)-U)**2-(PD(J)+U)**2
      Z(J)=1.-E*(GL(J)-U)/VO(J)
      GOTO 1000
C
C***  CODE 3: CORD GRAIN
 210  IF(I.GT.0) GOTO 220
      PD(J)=0.
      WI(J)=0.
      WO(J)=0.
      WM(J)=0.
      VO(J)=GL(J)*D(J)**2
 220  Z(J)=1.-AMAX1(GL(J)-U,0.)*(AMAX1(D(J)-U,0.))**2/VO(J)
      GOTO 1000
C
C***  CODE 9: ROUND-HEX 19-PERF GRAIN
 240  SO=13.
      SI=24.
      GOTO 260
C
C***  CODE 7: ROUND-HEX 37-PERF GRAIN
 250  SO=18.
      SI=54.
 260  WW=WI(J)+PD(J)
      WW2=WW**2
      PRFD=PD(J)+U
      PRFD2=PRFD**2
      GRL=AMAX1(GL(J)-U,0.)
      WOD=WO(J)
      E=0.
      THETA=2.*ACOS(AMIN1(WW/PRFD,1.))
      ALPHA=ACOS(AMIN1((2.*WOD+PD(J)-U)/PRFD,1.))
      IF(U.LT.WOD) E=.25*PI*((2.*WOD+PD(J)-U)**2-PRFD2)
      IF(THETA.GE.PI3) GOTO 270
      E=E+SI*.25*(WW2*RT-1.5*PRFD2*(SIN(THETA)+PI3-THETA))
 270  IF(ALPHA.GE. .5*(PI-THETA)) GOTO 280
      E=E+SO*.125*(2.*(2.*WOD+PD(J)-U)*(2.*WW-PRFD*SIN(ALPHA))-PRFD2*
     1(SIN(THETA)+PI-2.*ALPHA-THETA))
 280  IF(I.GT.0) GOTO 290
      WM(J)=WI(J)
      IF(N(J).EQ.10) D(J)=3.*PD(J)+2.*WI(J)+2.*WOD
      IF(N(J).EQ.8) D(J)=5.*PD(J)+4.*WI(J)+2.*WOD
      IF(N(J).EQ.7) D(J)=7.*PD(J)+6.*WI(J)+2.*WOD
      VO(J)=E*GL(J)
      IF(2.*WOD+PD(J).GE.WI(J)) GOTO 290
      CALL ERRMSG('*FORMT* BAD HEX PROP')
 290  Z(J)=1.-E*GRL/VO(J)
      GOTO 1000
C
C***  CODE 9: 19-PERF GRAIN
 310  IF(I.GT.0) GOTO 320
      D(J)=5.*PD(J)+2.*(WI(J)+WM(J)+WO(J))
      VO(J)=.25*PI*GL(J)*(D(J)**2-19.*PD(J)**2)
      DO 315 K=1,4
      IFLAG(K,J)=-1
 315  CONTINUE
```

```
      SF(1,1,J)=WI(J)+PD(J)
      SF(2,1,J)=SF(1,1,J)
      SF(3,1,J)=SF(1,1,J)
      SF(1,2,J)=.5*SQRT(3.*(WM(J)+PD(J))**2+(WI(J)+PD(J))**2)
      SF(2,2,J)=SF(1,2,J)
      SF(3,2,J)=SF(1,1,J)
      SF(1,3,J)=PD(J)+.5*(WI(J)+WM(J))
      SF(2,3,J)=SF(1,2,J)
      SF(3,3,J)=WM(J)+PD(J)
      SF(1,4,J)=SF(1,3,J)
      SF(2,4,J)=2.*SF(1,3,J)
      SF(3,4,J)=SF(1,3,J)*RT
      WEBC(J)=AMIN1(WO(J),WM(J),WI(J),SF(1,3,J)-PD(J),SF(1,2,J)-PD(J),
     $GL(J))
  320 GRL=AMAX1(GL(J)-U,0.)
      DD=D(J)-U
      PRFD=PD(J)+U
      IF(U.GT.WEBC(J)) GOTO 330
      E=.25*PI*(DD**2-19.*PRFD**2)
      Z(J)=1.-GRL*E/VO(J)
      GOTO 1000
  330 DO 340 K=1,3
      CALL GENIS(SF(1,K,J),AW(1,K,J),PRFD,GRL,IFLAG(K,J),GV(K,J))
  340 CONTINUE
      CALL GENOS(SF(1,4,J),AW(1,4,J),PRFD,GRL,.5*DD,IFLAG(4,J),GV(4,J))
      Z(J)=1.-(6.*(GV(1,J)+GV(2,J))+12.*(GV(3,J)+GV(4,J)))/VO(J)
      GOTO 1000
C
C***  CODE 4: RECTANGULAR STRIP GRAIN
  430 IF(I.GT.0) GOTO 440
      PD(J)=0.
      WO(J)=0.
      WM(J)=0.
      VO(J)=GL(J)*D(J)*WI(J)
  440 Z(J)=1.-AMAX1(GL(J)-U,0.)*AMAX1(D(J)-U,0.)*
     $AMAX1(WI(J)-U,0.)/VO(J)
      GOTO 1000
C
C***  CODE 5: SPHERICAL GRAIN
  450 IF(I.GT.0) GOTO 460
      GL(J)=0.
      PD(J)=0.
      WI(J)=0.
      WO(J)=0.
      WM(J)=0.
  460 Z(J)=1.-(AMAX1(D(J)-U,0.)/D(J))**3
      GOTO 1000
C
C***  CODE 6: SLOTTED-TUBE GRAIN
  500 IF(I.GT.0) GOTO 510
      WO(J)=0.
      PRFD=.5*WM(J)
      SO=.5*D(J)
      SI=.5*PD(J)
      THETA=.5*PI-ACOS(PRFD/SO)
      ALPHA=.5*PI-ACOS(PRFD/SI)
      VO(J)=GL(J)*((PI-THETA)*SO**2-(PI-ALPHA)*SI**2-
```

```
     $PRFD*(SO*COS(THETA)-SI*COS(ALPHA)))
      WEBC(J)=AMIN1(GL(J),WI(J))
 510  E=0.
      IF(U.GT.WEBC(J)) GOTO 520
      PRFD=.5*(WM(J)+U)
      SO=.5*(D(J)-U)
      SI=.5*(PD(J)+U)
      BRL=GL(J)-U
      THETA=.5*PI-ACOS(PRFD/SO)
      ALPHA=.5*PI-ACOS(PRFD/SI)
      E=(PI-THETA)*SO**2-(PI-ALPHA)*SI**2-PRFD*(SO*
     $COS(THETA)-SI*COS(ALPHA))
 520  Z(J)=1.-E*BRL/VO(J)
      GOTO 1000
C
C***  CODE 10: ROUND-HEX 7-PERF GRAIN
 600  SO=6.
      SI=6.
      GOTO 260
C
 1000 CONTINUE
      RETURN
      END
```

```
C      GENIS.001       11-DEC-78
       SUBROUTINE GENIS(S,A,PRFD,GRL,IFLAG,VOL)
C
C   SUBROUTINE *GENIS*: CALCULATE SURFACE AREA AND VOLUME FOR A
C                       GENERAL INNER SLIVER OF A BURNING GRAIN
C                       WITH LENGTH = GRL & PERF DIAM = PRFD.
C
       DIMENSION S(3),A(4)
       DATA PI2/ 1.5707963 /
C
       IF(IFLAG) 10,20,30
C
C   INITIAL PASS: IFLAG WAS SET NEGATIVE BY CALLING ROUTINE.
C                 STORE ANGLES A1,A2,A3 AND AREA OF TRIANGLE
C                 WITH SIDES S(1),S(2),S(3) INTO A(1),...,A(4)
C
   10  A(1) = ACOS((S(2)**2+S(3)**2-S(1)**2)/(2.*S(2)*S(3)))
       A(2) = ACOS((S(1)**2+S(3)**2-S(2)**2)/(2.*S(1)*S(3)))
       A(3) = ACOS((S(1)**2+S(2)**2-S(3)**2)/(2.*S(1)*S(2)))
C
       A(4) = .5*S(1)*S(3)*SIN(A(2))
C
C   ...CHECK FOR ERROR CONDITION: FIND IF TRIANGLE ACCEPTABLE...
C
       J = 0
       DO 15 I = 1,3
       IF(A(I).LT..5*PI2) J = J+1
   15  CONTINUE
       IF(J.GT.1) CALL ERRMSG('*GENIS* ERROR             ')
C
C   IF OK, SET FLAG TO ZERO TO BYPASS INITIALIZATION HEREAFTER.
C
       IFLAG = 0
C
C   SUCCEEDING PASSES UNTIL BURNOUT: FIND AUXILIARY ANGLES
C
   20  TAU12 = ACOS(AMIN1(1.,S(3)/PRFD))
       TAU13 = ACOS(AMIN1(1.,S(2)/PRFD))
       TAU23 = ACOS(AMIN1(1.,S(1)/PRFD))
C
C   ...AND BRANCH IF SLIVER FAILS BURNOUT CRITERIA.
C
       IF(TAU12+TAU13+TAU23.LT.PI2 .AND. GRL.GT.0.) GOTO 25
C
C   SLIVER JUST BURNED OUT: SET FLAG TO BYPASS AREA & VOLUME CALCULATIONS
C
       IFLAG = 1
       GOTO 30
C
C   SLIVER NOT BURNED OUT: DETERMINE END AREA, VOLUME, AND SURFACE AREA
C
   25  E = A(4)-.25*PRFD*(S(1)*SIN(TAU23)+S(2)*SIN(TAU13)
      &+S(3)*SIN(TAU12)+PRFD*(PI2-TAU12-TAU13-TAU23))
C
       VOL = E*GRL
C
C      SURF = 2.*E+GRL*PRFD*(PI2-TAU12-TAU13-TAU23)
```

```
C
C   ...AND RETURN.
C
      RETURN
C
C   SLIVER IS BURNED OUT: RETURN WITH ZERO VOLUME AND SURFACE AREA.
C
   30 VOL = 0.
C     SURF = 0.
      RETURN
C
      END
```

```
C     GENOS.002        09-JUN-80
      SUBROUTINE GENOS(S,A,PRFD,GRL,RAD,IFLAG,VOL)
C
C  SUBROUTINE *GENOS*: CALCULATE SURFACE AREA AND VOLUME FOR A
C                      GENERAL OUTER SLIVER OF A BURNING GRAIN
C                      WITH LENGTH = GRL, RADIUS = RAD, AND
C                      PERF DIAM = PRFD.
C
      DIMENSION S(3),A(4)
C
      IF(IFLAG) 10,20,30
C
C  INITIAL PASS: IFLAG WAS SET NEGATIVE BY CALLING ROUTINE.
C                STORE ANGLES A1,A2,A3 AND AREA OF TRIANGLE
C                WITH SIDES S(1),S(2),S(3) INTO A(1),...,A(4)
C
   10 A(1) = ACOS((S(2)**2+S(3)**2-S(1)**2)/(2.*S(2)*S(3)))
      A(2) = ACOS((S(1)**2+S(3)**2-S(2)**2)/(2.*S(1)*S(3)))
      A(3) = ACOS((S(1)**2+S(2)**2-S(3)**2)/(2.*S(1)*S(2)))
C
      A(4) = .5*S(1)*S(3)*SIN(A(2))
C
C  ...AND SET FLAG TO ZERO TO BYPASS INITIALIZATION HEREAFTER.
C
      IFLAG = 0
C
C  SUCCEEDING PASSES UNTIL BURNOUT: FIRST DETERMINE AUXILIARY ANGLES
C
   20 TAU1 = ACOS(AMIN1(1.,(S(2)**2+RAD**2-.25*PRFD**2)/(2.*S(2)*RAD)))
      TAU2 = ACOS(AMIN1(1.,(S(3)**2+RAD**2-.25*PRFD**2)/(2.*S(3)*RAD)))
      TAU3 = ACOS(AMAX1(-1.,(S(2)**2-RAD**2+.25*PRFD**2)/(S(2)*PRFD)))
      TAU4 = ACOS(AMAX1(-1.,(S(3)**2-RAD**2+.25*PRFD**2)/(S(3)*PRFD)))
C
      SIG = ACOS(AMIN1(1.,S(1)/PRFD))
C
C  ...AND BRANCH IF SLIVER FAILS BURNOUT CRITERIA.
C
      IF(TAU1+TAU2.LT.A(1) .AND. GRL.GT.0.) GOTO 25
C
C  SLIVER JUST BURNED OUT: SET FLAG TO BYPASS AREA & VOLUME CALCULATIONS
C
      IFLAG = 1
      GOTO 30
C
C  SLIVER NOT BURNED OUT: FIRST CHECK ERROR CONDITIONS...
C
   25 IF(TAU3.LT.A(3) .OR. TAU4.LT.A(2))
     $ CALL ERRMSG('*GENOS* ERROR          ')
C
C  ...IF OK, DETERMINE END AREA, VOLUME, AND SURFACE AREA
C
      E = .5*RAD*(S(2)*SIN(TAU1)+RAD*(A(1)-TAU1-TAU2)+S(3)*SIN(TAU2))
     $-A(4)-.25*PRFD*(S(1)*SIN(SIG)+.5*PRFD*(TAU3+TAU4-2.*SIG
     $-A(2'-A(3)))
C
      VOL = E*GRL
C
```

```
C     SURF = 2.*E*GRL*(RAD*(A(1)-TAU1-TAU2)+.5*PRFD*(TAU3+TAU4-2.*SIG
C    $ -A(2)-A(3)))
C
C  ...AND RETURN.
C
      RETURN
C
C  SLIVER IS BURNED OUT: RETURN WITH ZERO VOLUME AND SURFACE AREA.
C
   30 VOL = 0.
C     SURF = 0.
      RETURN
C
      END
```

APPENDIX B

LIST OF SYMBOLS

LIST OF SYMBOLS

Symbol	Array	Description
M	N (NO)	Number of propellants
Z	Y (YES)	Fractions burned
ICFLAG	Y	Ignition threshold flags
N	Y	Grain codes
U	N	Twice depth burned
I	N	Flag, equals 0 on initial pass
VO	Y	Initial grain volumes
IFLAG	Y	Slivering flags
GV	Y	Sliver volumes
WEBC	Y	Overall grain webs
SF	Y	Work arrays
AW	Y	Work arrays
RT	N	3
PI	N	π
PI3	N	$\pi/3$
GL	Y	Grain lengths: all codes except 5
D	Y	Grain diameters: all codes except 4 Grain widths: code 4
PD	Y	Perforation diameters: codes 1,2,6,7,8,9
WI	Y	Inner webs: codes 1,2,6,7,8,9 Grain thicknesses: code 4
WM	Y	Middle webs: code 9 Slot widths: code 6
WO	Y	Outer webs: codes 1,7,8,9
WOD	N	Outer webs: codes 1,7,8,9

LIST OF SYMBOLS (cont'd)

Symbol	Array	Description
WW	N	Distance between perforation centers
WW2	N	WW · WW
GRL	N	Grain length - U
OD	N	Grain diameter - U
PRFD	N	Perforation diameter + U
PRFD2	N	PRFD · PRFD
E	N	End-area of grain
ALPHA, THETA	N	Various angles

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